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PARIS SCHOOL OF ECONOMICS  
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## WORKING PAPER N° 2024-45

### Does economic convergence challenge global climate goals?

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JEL Codes: Q54, H23, O11, O47, Q43

Keywords: Climate change, Environmental policy, Economic convergence,  
Green technologies

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## Does economic convergence challenge global climate goals?

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### Highlights

- We simulate scenarios to test how to reach climate targets in the context of economic convergence
- Under economic convergence, the world does not reach climate goals with strong carbon tax policies only
- Both energy price policies and large-scale deployment of green technologies are necessary
- Economic convergence reinforces the need for ambitious hybrid climate policies

### Abstract

We employ the ACCL model for climate policy simulation to investigate the feasibility of achieving climate targets in the context of global economic convergence. Our findings indicate that, in a scenario with moderate economic convergence, the world does not reach these targets solely with ambitious, although realistic, energy price policies. Our estimates underscore the importance of combining global carbon taxation with the widespread deployment of green technologies to help reconcile economic convergence and climate objectives. Hence, initiatives that focus on accelerating the global energy transition and supporting its implementation in low- and middle-income countries are crucial with regard to this challenge.

**JEL classification:** Q54, H23, O11, O47, Q43

**Keywords:** climate change, environmental policy, economic convergence, green technologies

## 1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC, 2022a), world temperatures exceeding the 1.5°C threshold above pre-industrial levels worsens dramatically global warming damages. Anthropogenic global warming currently increases at an unprecedented rate of 0.23°C per decade (Forster *et al.*, 2023). Hence, more than 120 countries have pledged a net-zero emission target for 2030 to 2070, depending on the country (Fankhauser *et al.*, 2022). Yet, these global climate objectives may conflict with the economic development goals of low and middle-income regions.

This study explores the relationship between economic convergence and the environment. As Brock and Taylor (2003) underline, “Growth theory offers us the tools needed to explore the link between environmental problems of today and the likelihood of their improvement tomorrow”. For example, Karakaya *et al.* (2019) replicate the results of Strazicich and List (2003) and show that carbon dioxide (CO<sub>2</sub>) emissions converge in their chosen countries. What is at stake here is the “environmental catch-up” hypothesis, which refers to the “convergence of environmental quality” between rich and poor countries at a point in time. The Environmental Kuznets Curve (EKC) explains this behaviour. According to the EKC, the countries that will reduce their CO<sub>2</sub> emissions are those which have reached a specific income level. As long as these countries are below this level, more Gross Domestic Product (GDP) will lead to more emissions *per capita* (Strazicich and List, 2003).

Contrary to this strand of literature, we focus here on beta convergence<sup>1</sup> issues and their implications for climate objectives. Our contribution addresses the fundamental challenge: how could the world achieve climate objectives without renouncing economic convergence for low and middle-income countries?

Low- and middle-income regions converge towards rich countries since the mid-1990s (Patel, Sandefur, and Subramanian, 2021), while the convergence between high-income economies is halting well below the US GDP *per capita* level (Bergeaud, Cette, and Lecat, 2020). However, Patel, Sandefur, and Subramanian (2021) argue that the catching-up from poorer regions mainly comes from their speeding and steadier growth, especially for middle-income countries, rather than the growth slackening in wealthier economies. Using country panels since 1870 and 1960, Barro (2015) estimates the GDP *per capita* annual conditional convergence rate to be near the 2% ‘iron law’. Yet, the International Monetary Fund (IMF, 2024) predicts a slowing down of the expansion pace and sheds light on the lingering economic inequalities with the rest of the world.

Global warming will severely raise these spatial disparities (Cruz and Rossi-Hansberg, 2024). Indeed, according to the Organisation for Economic Co-operation and Development (OECD, 2015), low-income regions are the most vulnerable to global warming, even though high-income countries are the highest historical emitters of greenhouse gases (GHG) (IPCC, 2022b).

In this context, climate mitigation measures should consider environmental, as well as development and equity concerns. While Hassler and Krusell (2012) find that carbon taxes on oil-producing - rather than oil-consuming - regions improve global climate, Känzig *et al.* (2024) show evidence of carbon leakages from Europe to Africa when increasing carbon prices in the former. Acemoglu *et al.* (2012) thus insist on the merit of international policy coordination for carbon taxes and directed research subsidies in both the North and South. Barrett (2021) goes one step further on the need to combine these coordinated global mitigation policies with international technology diffusion. According to Belfiori and Macera (2024), ‘green’ technologies like carbon capture may even tackle climate inequality as a redistribution tool when direct transfers across countries are impractical.

Indeed, several papers regard coupling emission tax with regional (and potentially generational) transfers as the optimal climate policy (Kotlikoff *et al.*, 2024; Hillebrand and Hillebrand, 2019, and 2023). Pareto-improving transfers can simultaneously share the burden of climate change and act as an incentive to join global climate agreements (Hillebrand and Hillebrand, 2019 and 2023). Yet, Chouard and Kablan (2022) show that climate-related financial aid matters for reducing CO<sub>2</sub> emissions in some recipient countries struggling to boost their economic growth, but up to a certain threshold. For Herzer and Schmelmer (2023), South-South Foreign Direct Investments (FDI) are the ones to diminish low- and middle-income countries’ energy intensity, not North-

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<sup>1</sup> Here, beta convergence corresponds to partial GDP *per capita* convergence to the US level: GDP *per capita* growth is positively correlated to the gap between the US GDP *per capita* level and the one of the country.

South FDI. Finally, institutional constraints may also limit the effectiveness of mitigation policy packages to reach climate targets (Bertram *et al.*, 2024). Addressing climate change efficiently and equitably thus requires international cooperation, coordination, and solidarity.

Using the ACCL<sup>2</sup> model (Alestra *et al.* 2022) for climate policy simulation, we perform scenarios to test how to reach climate targets under economic convergence. Since there is no consensus in this literature, we contribute by offering additional estimates - as accurate and transparent as possible - with a global and long-term perspective relevant to policy decisions. Our model is particularly well-suited to study the interaction between climate and convergence objectives as it provides a comprehensive endogenous modelling of economic activity and highly disaggregated outcomes. Indeed, we estimate the GDP growth and Total Factor Productivity (TFP) dynamics with various energy sources and 31 distinct countries or regions. We contrast scenarios of different development paths, climate mitigation policies and 'green' technologies individually and simultaneously until 2100. We find that economic convergence increases GHG emissions and makes it more challenging to achieve these climate objectives, even with global carbon taxation. Hence, to both reach these targets and allow low-income countries to catch up, it is necessary to implement hybrid policies combining carbon tax and green technology transfers.

The remainder of the paper proceeds as follows. Section 2 specifies the methodology used to simulate climate-related policies and economic convergence. Section 3 presents the results of our three scenarios, and finally, Section 4 concludes.

## 2. Methodology

### 2.1. ACCL model and data presentation

The ACCL model is a [free-access model](#) that allows the user to quantify the consequences of different types of policies and shocks (for instance, energy prices and technological policies and shocks) on the GDP. ACCL uses an original database that enables the estimation and calibration of the model relationships in 18 developed countries, seven emerging countries, and six regions covering the rest of the world. ACCL allows the implementation of global and local projections for the whole world at the 2060 and 2100 horizons. ACCL distinguishes five types of energy, four 'dirty' in terms of CO<sub>2</sub> emissions (coal, petrol, gas, 'dirty' electricity) and 'clean' electricity. The ACCL model adopts a supply-side approach and a long-term view. At the long-term 2060 and 2100 horizons, ACCL assumes full capacity utilisation and adjustment of production factors to their optimum values.

We compile various sources in our novel database including the Long-Term Productivity Database (Bergeaud, Cette, and Lecat, 2016), Koske *et al.* (2015), the OECD Economic Outlook (2018) and Employment Outlook (2018) and national statistics for economic variables. Regarding education and demographic characteristics, we employ the United Nations (UN) population projections and the United Nations Educational, Scientific and Cultural Organization (UNESCO) database. For our energy and environmental variables, we match data from the International Energy Agency (IEA) Headline Global Energy Data (2017) and Energy Prices and Taxes database (2018), Koffi *et al.* (2017), Marland, Boden, and Andres (2017), David Stern's meta-analysis (2012), Papageorgiou *et al.* (2017) and the OECD (2015).<sup>3</sup>

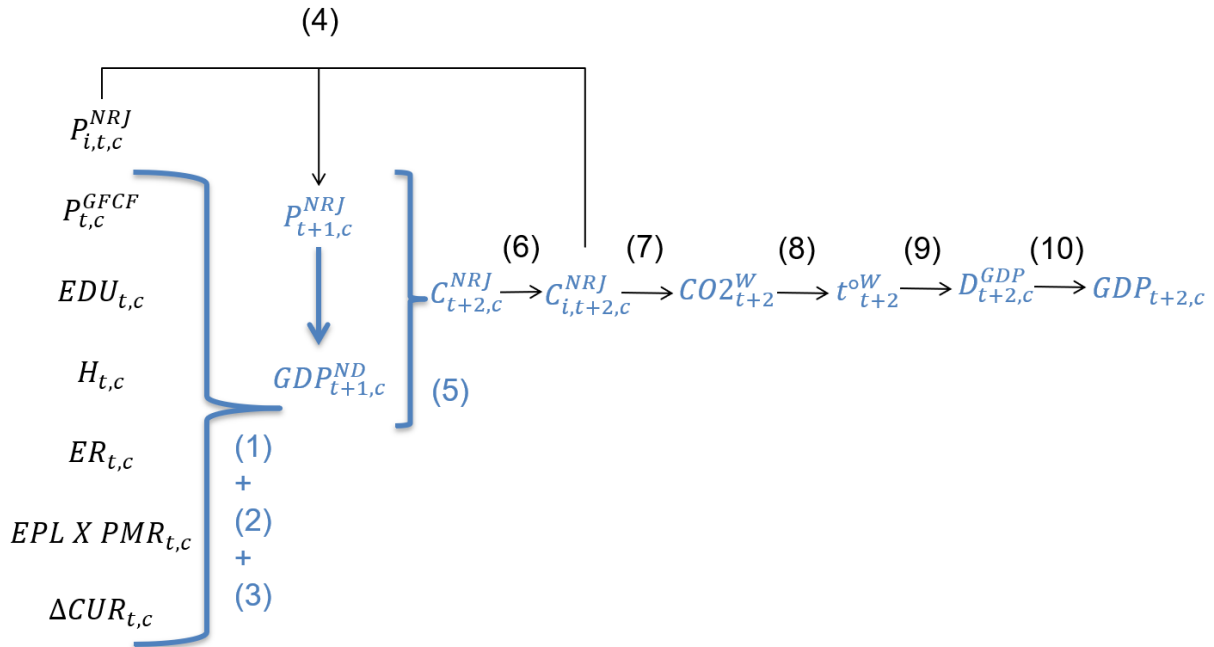
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<sup>2</sup> Advanced Climate Change Long-term model.

<sup>3</sup> See Alestra *et al.* (2022) for more detailed information on data sources.

Figure 1 presents the overall scheme of the projection tool. The main input series (cf. Table 1) are in black, and the resulting output series are in blue.

**Figure 1**  
Overall scheme of the projection tool



Subscript  $i$  for energy type  $i$ ,  $t$  for year and  $c$  for country. Numbers correspond to specific relations, estimated relationship numbers in blue and calibrated or accounting ones in black. These relations are presented in Appendix 1.

**Table 1**  
Main series used in the scenario tool

**Scenarios hypotheses**

- $P_{t,c}^{NRJ}$ : Relative energy prices
- $P_{t,c}^{GFCF}$ : Relative investment price
- $EDU_{t,c}$  Mean years of education
- $H_{t,c}$  Average hours worked per employee
- $ER_{t,c}$  Employment rate
- $EPL * PMR_{t,c}$  Regulation index
- $\Delta CUR_{t,c}$  Change in capacity utilisation rates

**Results from estimated, calibrated or accounting relationships**

- $GDP_{t,c}$  Gross Domestic Product in volume and Purchasing Power Parity 2010
- $C_{t,c}^{NRJ}$  Energy final consumption
- $CO2_t^W$  World CO<sub>2</sub> emissions
- $t_t^{oW}$  Increase in world temperature from pre-industrial era
- $D_{t,c}^{GDP}$  Damage to GDP from global warming in country  $c$

Important inputs are the prices of the different types of energy relative to the GDP price. These series are meant to represent the policies that will impact the relative price of energy sources to curb energy consumption towards less CO<sub>2</sub>-emitting energy types. For each country or region, TFP and then GDP depend, among other factors, on the energy price relative to the GDP price, corresponding to a substitution effect. If this relative price increases, firms decrease their intermediate energy consumption and increase their use of labour and capital production factors per unit of GDP. Everything else being equal, it leads to a decrease in the TFP. This specification is consistent with several models, like the DICE (Dynamic Integrated Climate-Economy) model of Nordhaus (2018) for instance. TFP also depends on linear time trends, which can be changed for each country and the two long-term sub-periods to introduce our productivity convergence scenarios.

GDP is based on a Cobb-Douglas production function with two factors: capital and labour. TFP is estimated based on its structural determinants as well as on relative energy prices: Relation (1) of diagram 1 is the long-term estimates of TFP on all the series defined in the scenario mentioned above except regulations, which are used in Relation (2) as determinants of the country fixed effects estimated in Relation (1), and capacity utilisation rate, which are used in short-run Relation (3). Labour is directly determined by the hypotheses on employment rates and hours worked. We endogenise the capital stock dynamics from the path of TFP, labour and relative investment prices. Relation (5) relates total energy consumption to relative energy prices and GDP. The decomposition of total energy consumption into consumption of the different energy types is based on the substitution elasticities between energy types, which are set as parameters of the scenarios (Relation (4) and (6)). As energy prices influence the TFP level, our production function indirectly corresponds to one with three production factors, with an implicit substitution elasticity between energy and the other two factors not necessarily equal to one.

Consumption by energy types and country/region yields a path of global CO<sub>2</sub> emissions (Relation (7)). The relationship between the GHG stock and global temperature increase compared to the pre-industrial era (Relation (8)) is calibrated on the Representative Concentration Pathway of the IPCC (2014). GDP damage from temperature increase is calibrated on Nordhaus and Moffat's (2017) meta-analysis of studies and derived at the country/region level using OECD (2015) estimates as a distribution key. GDP damage is assumed to be non-linearly related to temperature increases (Relation (9)). We suppose that GDP damage from temperature increase does not affect the energy consumption stemming from GDP, as it results from it. Indeed, this damage may appear non-linearly through time and hence may not slow down energy consumption.

Three types of climate-oriented technical progress are considered: energy efficiency gains, the deployment of non-CO<sub>2</sub>-emitting energies and carbon capture (these technologies are more detailed below). The first of these three types of climate-oriented technical progress is introduced through changes in Relation (5), and the two others are introduced through changes in Relation (7).

## 2.2 Convergence modelling

Economic convergence is modelled here as beta GDP *per capita* convergence. We assume each laggard country (high- or low-income) catch up half of the initial GDP *per capita* gap with the US by 2100. To introduce this partial convergence of the GDP *per capita* of the different countries to the US GDP *per capita* level, we first evaluate the change of GDP growth to which this partial convergence corresponds for each country  $c$  ( $\delta q_c$ ). The evaluation of this change is detailed below (in Section 3.2). The partial convergence is introduced through a change in the TFP growth rate. So, we evaluate the corresponding change in the TFP growth rate ( $\delta tfp_c$ ) that has to be introduced to obtain the expected change in the GDP. From the equations of the ACCL model (and more precisely from Relations (1') and (2'), see Appendix 1), this change in the TFP growth rate corresponds to the relation:

$$\delta tfp_c = \delta q_c \cdot (1 - \alpha)$$

Where  $q$  and  $tfp$  correspond respectively to the log of the GDP ( $Q$ ) and of TFP,  $\delta$  to the constant extra growth rate associated to the economic convergence process and  $\alpha$  to the elasticity of the output  $Q$  to the capital  $K$ . For reasons detailed in Alestra *et al.* (2022), ACCL assumes a constant elasticity over time for all countries with the calibration:  $\alpha = 0.3$ .

## 3. Results

### 3.1. Business as usual and energy price scenarios

Simulations done with ACCL indicate that, without climate policies, if the relative price of each of the five energy types remains stable, which corresponds to a 'Business as usual' (BAU) scenario, the global warming may be almost +5°C in 2100, with significant climate damages (nearly 11% in terms of GDP at the world level), particularly in India, Middle East, China or Africa (see Figures 2 and 3.1). Hence, we notice high spatial disparity

in climate damages around the world. Canada and Russia even display a positive impact from global warming from the supply-side gains of arable land expansion with the temperature growth. Yet, we can consider this evaluation optimistic, as it assumes no tipping points which would amplify the warming and, thus, the damages.

To intervene only through the relative price of the different energy types requires challenging hypotheses concerning the price increase of 'dirty' energy (through, for instance, a carbon tax) and the price decrease of 'clean' energy (through technical progress and subsidies) to reach the climate goal of staying below a 2°C warming at the end of the XXI<sup>st</sup> Century. We test an energy price scenario of a 2% per year increase of the relative price of the four 'dirty' energy types associated with a decrease of 1% per year of the relative price of the 'clean' energy type. But in this Energy Price Policies (EPP) scenario, the world does not reach climate goals, with a global warming of about 2.5°C in 2100 and highly significant damages in some regions such as India, with 5% of GDP damages (see Figures 2 and 3.2). Hence, technological support is essential to achieve those climate goals (see Alestra *et al.*, 2023).

### 3.2 Convergence results

The BAU or EPP scenarios account for three factors supporting GDP growth: a worldwide decrease in the relative price of investment, modelling general technological progress, and based on the historical trend; population growth based on United Nations demographic projections, which supports employment growth in most countries; convergence of education levels, sustaining TFP in the ACCL model. Yet, beyond these growth-supporting factors, economic convergence, proceeding through the diffusion of existing technologies and best practices, may foster growth in countries with low GDP *per capita*. Indeed, Barro (2015), among others, found conditional beta-convergence on several country panels, supporting the 'iron law' of a 2% rate of convergence, i.e. half of an initial gap in GDP *per capita* vanishes in 35 years. Convergence is conditional on several factors (institutional factors such as the rule of law or democracy or structural factors like trade openness), which most laggard countries do not meet. Hence, we model a prudent scenario of slower Economic Convergence (EC scenario) by adding a country-specific trend in the TFP equation: half the initial gap between each laggard country (high- or low-income) and the US vanishes at the 2100 horizon, leading to a world growth rate without the US of 2.4% a year, equivalent to observed trend since 2000.

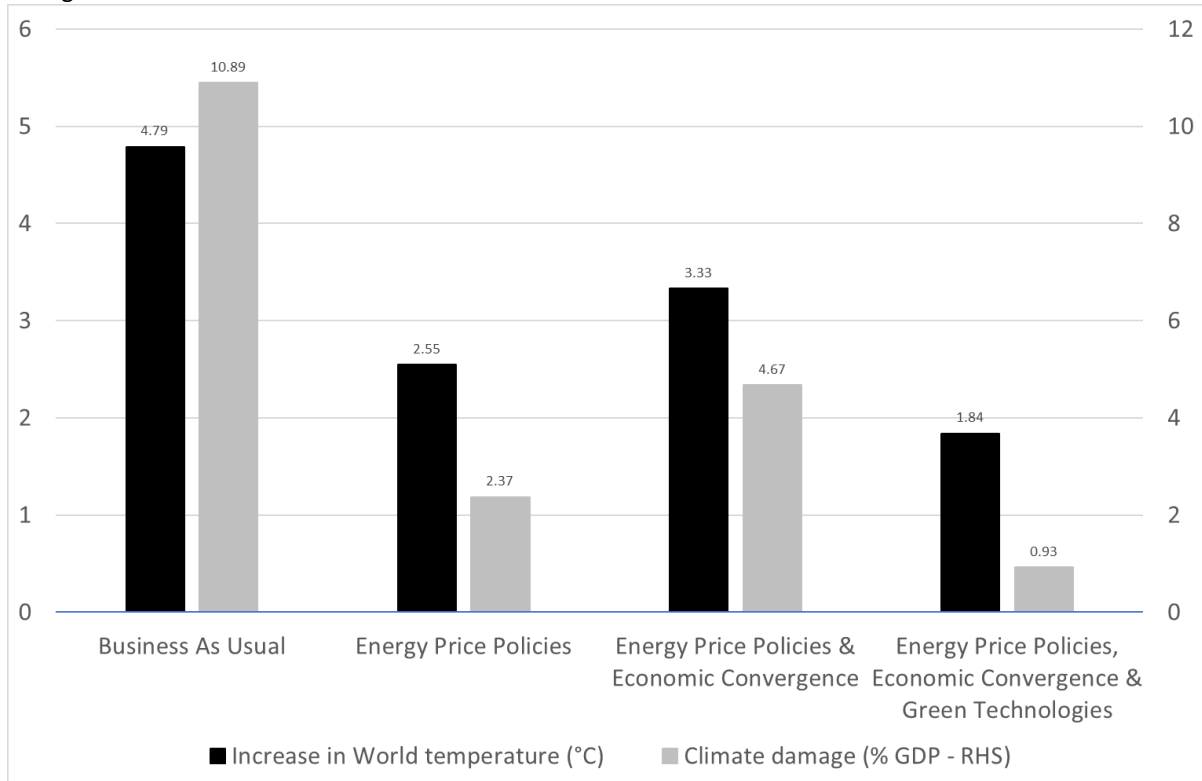
Yet, even in this prudent EPP & EC scenario, economic convergence deteriorates significantly the climate outcome (see Figures 2 and 3.3). By 2100, world temperature is 0.8°C higher and climate damages are 2.3 pp higher on average, with far higher damages in climate-change-exposed countries such as India (5 pp higher corresponding to -10% damages). Indeed, higher economic growth in non-US countries leads to higher energy consumption, which has a close-to-unity elasticity to GDP (0.97). The EPP scenario tilts energy consumption towards non-CO<sub>2</sub> emitting sources both by increasing the average price of energy and through the price elasticity of substitution between energy sources. Yet, the overall elasticity of energy consumption to GDP effect dominates, leading to higher consumption of CO<sub>2</sub>-emitting energy sources. Hence, there appears to be a trade-off between climate goals and economic convergence, even at a slow rate. However, this result is due to an economic convergence that relies on the diffusion of non-climate-specific technologies.



**Figure 2**

**2100 increase in world temperature and climate damages in the different scenarios**

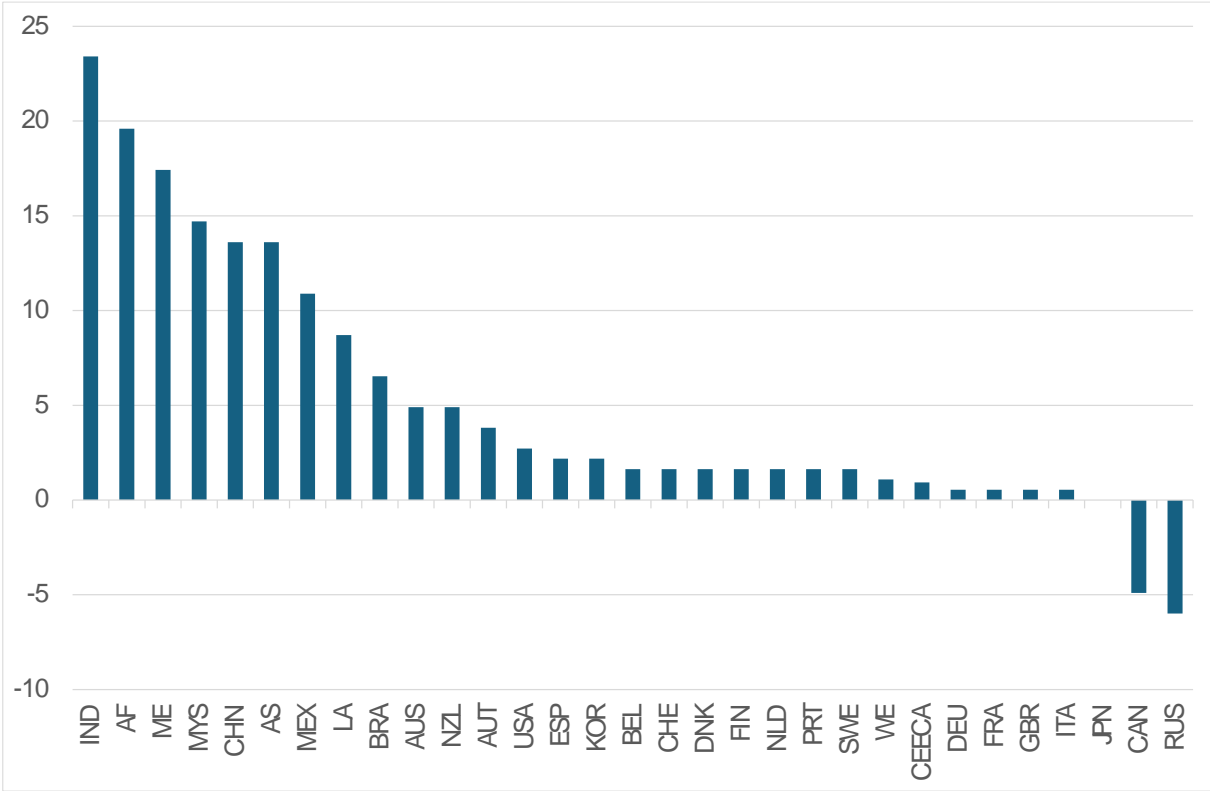
Left-hand scale in °C for the increase in world temperature and right-hand scale in % of GDP for climate damage.



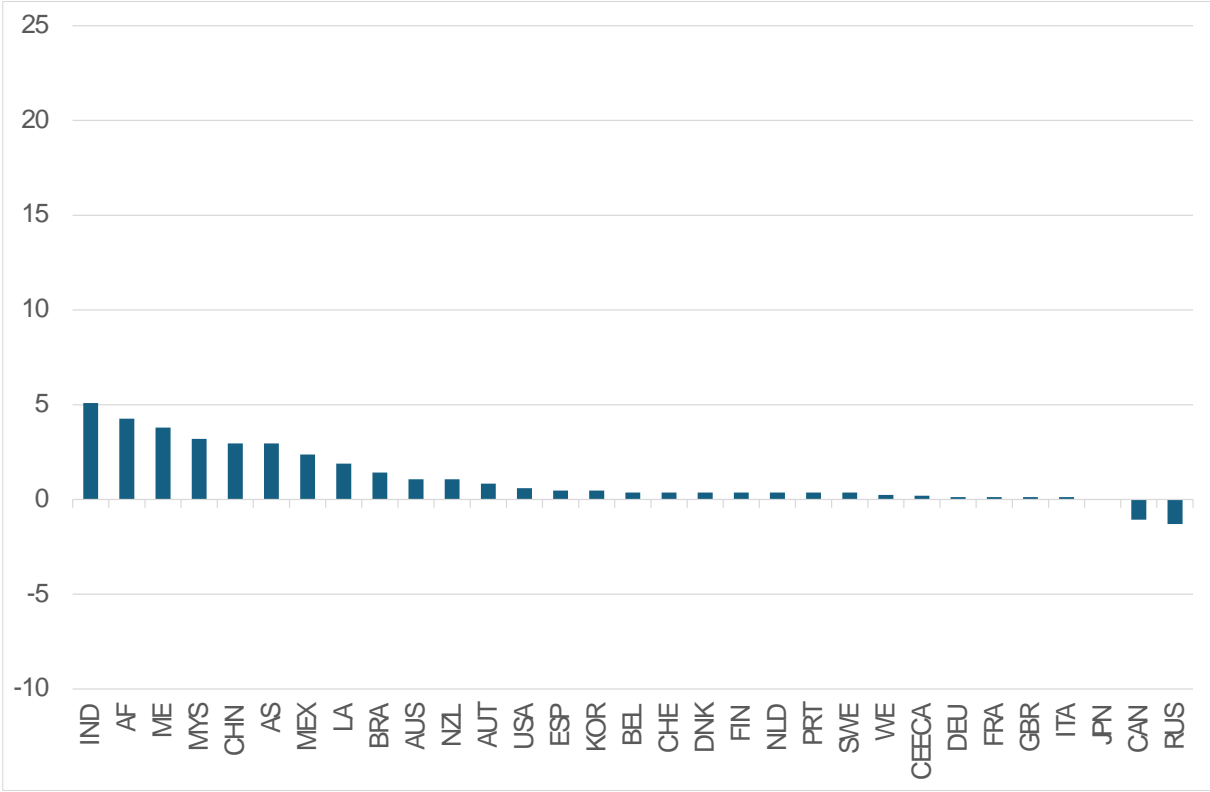
*Energy Price Policies (EPP): Increase by 2% per year of the relative price of the different types of CO<sub>2</sub> emitting energies and decrease by 1% per year of the non-emitting type of energy; Economic Convergence (EC): catch-up of 50% of the GDP per capita gap of each country compared to the US in 2100, before climate damages; Green Technologies (GT): decrease by 2% per year of the relative price of non-emitting energy (instead of 1% in EPP), energy efficiency gains of 1.6% per year and carbon sequestration of 4.49 Gt a year.*

**Figure 3**  
**2100 climate damages (% of GDP) in the different scenarios by country/region**

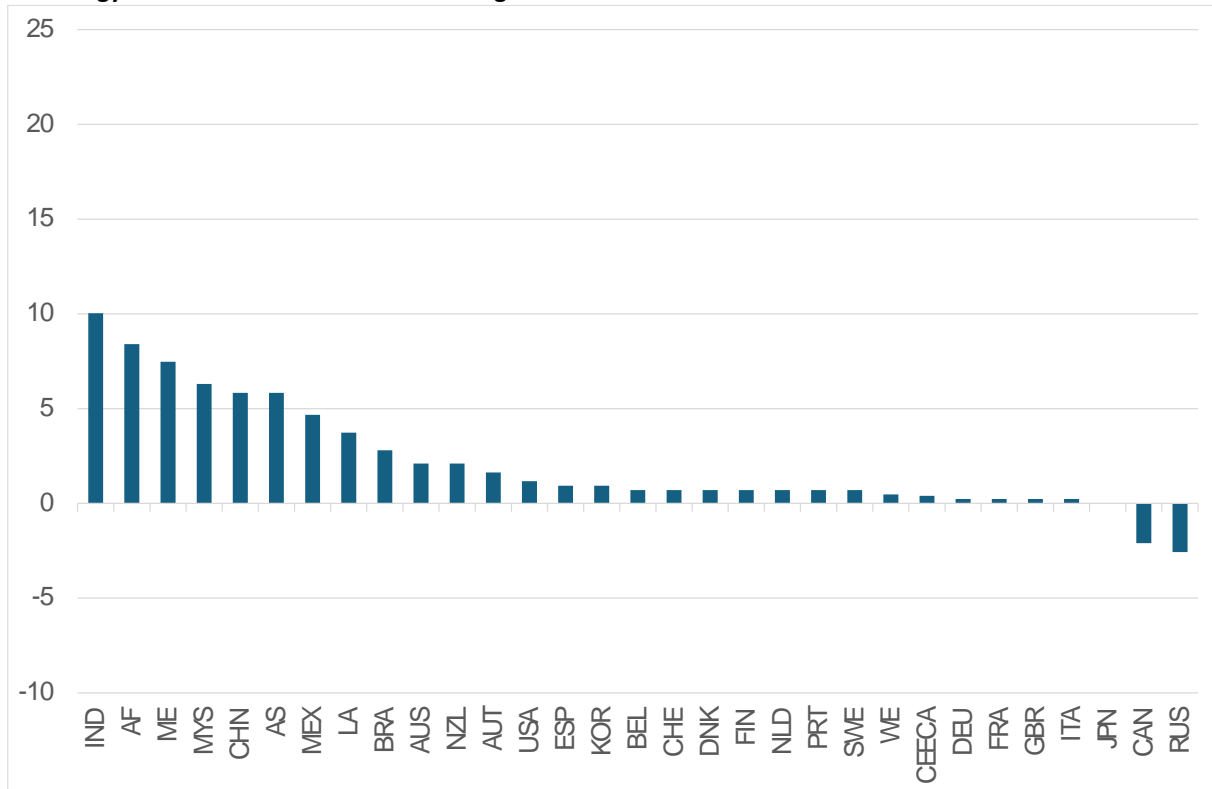
**3.1 Business as Usual**



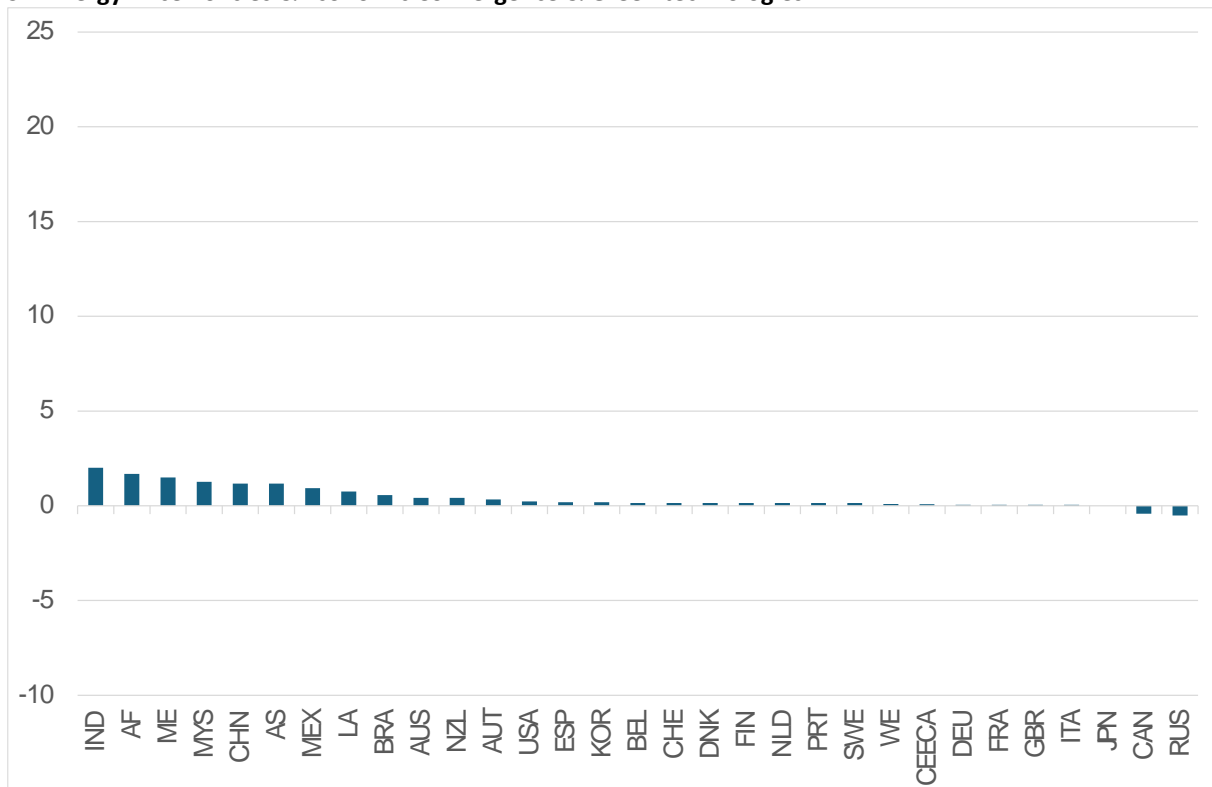
**3.2 Energy Price Policies**



### 3.3 Energy Price Policies & Economic Convergence



### 3.4 Energy Price Policies & Economic Convergence & Green technologies



Energy Price Policies (EPP): Increase by 2% per year of the relative price of the different types of CO<sub>2</sub> emitting energies and decrease by 1% per year of the non-emitting type of energy; Economic Convergence (EC): catch-up of 50% of the GDP per capita gap of each country compared to the US in 2100, before climate damages; Green

*Technologies (GT): decrease by 2% per year of the relative price of non-emitting energy (instead of 1% in EPP), energy efficiency gains of 1.6% per year and carbon sequestration of 4.49 Gt a year.*

### 3.3 Transfer of Green technologies

In their pathways, IPCC (2022a) and the IEA (2021) emphasise the crucial role of green technological progress in reaching climate objectives. We compute a third scenario to test whether the global diffusion of such green innovations can help reconcile economic convergence and climate targets. Hence, we combine energy price policies (EPP scenario), economic convergence (EC scenario) and the dissemination of Green Technology (GT scenario). We consider three types of climate-oriented technical progress simultaneously. We assume the deployment of non-CO<sub>2</sub>-emitting energies representing, for example, electrification, boosting renewable power generation, clean hydrogen, modern biomass or improved storage capacities. We also focus on energy efficiency gains, that is, the reduction in the ratio of energy use to GDP (like building renovation or enhanced batteries). Finally, we account for carbon capture, utilisation and storage techniques, i.e. all activities to separate CO<sub>2</sub> at emission or in the air, use it in extraction or industrial processes or store it in natural facilities. Our green technical progress thus encompasses both uncertain future innovations and the diffusion of already existing technologies. We model a decrease of 2% per year of the relative price of non-CO<sub>2</sub>-emitting energy (instead of 1% in the EPP scenario), energy efficiency gains of 1.6% per year and carbon sequestration of 4.49 Gt a year globally.<sup>4</sup>

In Figures 2 and 3.4, we find that our final EPP & EC & GT scenario almost reaches net zero carbon emissions, limiting the increase in world temperatures by 1.84°C in 2100 compared to the pre-industrial era, corresponding to climate damages of 0.93% on global GDP (and 2% for the Indian GDP, the worst affected country in our sample). Hence, our results suggest we may overcome the trade-off between economic convergence and climate goals by coupling ambitious energy price policies and between-country transfers in green technology. Our model is supply-sided, but we can suppose that high-income economies partially redistribute their carbon tax revenues to fund green transition in low- and middle-income regions.

## 4. Conclusion and Discussion

In this study, we perform our ACCL model to illustrate the trade-off between decarbonisation objectives and economic convergence. We highlight the importance of quantifying the impact of convergence on the capacity of countries to reach climate goals in order to measure the role of global green solutions. Indeed, economic convergence reinforces the need for both ambitious energy price policies and large-scale deployment of green technologies: our estimates point that the impact of convergence on carbon emission, calibrated on a moderate path, implies that carbon price policies solely cannot achieve climate goals. This result is in line with the conclusion of the World Economic Forum Annual Meeting (Molina *et al.*, 2024), stating that “A decoupling of emissions from economic growth needs to accelerate dramatically. As economies decarbonise, they also need to create jobs and raise incomes and living standards. This will be particularly important in developing and emerging economies (EMDEs). This is the true challenge of our times.”

Initiatives that focus on accelerating the global energy transition and supporting its implementation in low- and middle-income countries are hence crucial with regard to this challenge. Launched in 2021 and 2022 in South Africa and Indonesia, the Just Energy Transition Partnerships (JETP) represent current initiatives of international cooperation with respectively \$8.5 and \$20 billion of joint financial contributions to national energy transitions. These actions are in the spirit of the Conference of Parties’ financial commitment of high-income countries to help low and middle-income economies to decarbonise, develop their renewables and increase their resilience to climate damages.

Finally, our scenario policy assumptions remain challenging, requiring an ambitious, immediate, and global implementation, especially since our estimates probably undervalue climate risks, as they do not fully account for tipping points and extreme weather events.

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<sup>4</sup> See Alestra *et al.* (2023) for more details on our hypotheses of green technology.

## Data availability

Data are available [here](#).

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## Appendix 1

### The main relations of the ACCL model

The ACCL model is a [free-access model](#) which uses an original database that enables estimating and calibrating the model relationships over 18 developed countries, seven emerging countries, and six regions covering the rest of the world. Below, we remind the main relations of the ACCL model, which are presented in a more detailed way in Alestra *et al.* (2022). The number of each relation corresponds to the Figure 1.

The GDP evaluation is based on a supply-side model at the country level through a usual two-factor (capital and labour) Cobb-Douglas production function, with constant returns to scale:

$$(1) \quad Q_{c,t} = TFP_{c,t} \cdot K_{c,t-1}^{\alpha} \cdot (N_{c,t} \cdot H_{c,t})^{1-\alpha}$$

Where  $c$  and  $t$  variable indexes indicate for which country  $c$  and which year  $t$  the variable is considered.  $Q$  is the volume of GDP,  $TFP$  is the total factor productivity,  $K$  is the volume of capital installed at the end of the year,  $N$  is the employment, i.e. the number of workers, and  $H$  is the average number of hours worked per year and per worker.  $\alpha$  is the elasticity of output  $Q$  to capital  $K$ , and ACCL assumes a constant elasticity over time for all countries with the calibration:  $\alpha = 0.3$  as in other studies.

Relation (1) can be expressed in logs and growth rate terms:

$$(1') \quad \Delta q_{c,t} = \Delta t f p_{c,t} + \alpha \cdot \Delta k_{c,t-1} + (1 - \alpha) \cdot (\Delta n_{c,t} + \Delta h_{c,t})$$

Where  $x$  corresponds to the logarithm of the variable  $X$  ( $x = \log(X)$ ), and  $\Delta x$  is the usual approximation for the growth rate of  $X$ . ( $\Delta k_{c,t-1} - \Delta n_{c,t} - \Delta h_{c,t}$ ) is the change of the capital intensity, which corresponds to the capital deepening mechanism.

Employment  $N$  and working hours  $H$  are exogenous. The quantification of capital volume  $K$  and  $TFP$  is based on specific assumptions and relations.

Concerning  $K$ , the volume of capital, ACCL assumes that in the long term, at the potential path, the capital coefficient (ratio of capital divided by GDP) remains constant in nominal terms:

$$(2) \quad \Delta p q_{c,t} + \Delta q_{c,t} = \Delta p k_{c,t} + \Delta k_{c,t-1}$$

Where  $P_Q$  is the GDP price ( $pq = \log(P_Q)$ ) and  $P_K$  is the investment price in fixed productive capital ( $pk = \log(P_K)$ ).

From relation (2), we obtain the relation (2'), which is used to build long-term capital scenarios:

$$(2') \quad \Delta k_{c,t-1} = \Delta p q_{c,t} + \Delta q_{c,t} - \Delta p k_{c,t}$$

Total factor productivity (TFP), estimated in log level, depends on several variables:

$$(3a) \quad t f p_{c,t} = -0.023^* \cdot [pen - pgdp]_{c,t-1} + -0.370^{***} \cdot [pinv - pgdp]_{c,t-1} + 0.05 \cdot EDUC_{c,t-1} + -0.401^{***} \cdot ER_{c,t-1} + FE_c + \delta t f p_c \cdot I_{2016,t} + \varepsilon_{c,t}^5$$

Where  $pen$ ,  $pgdp$  and  $pinv$  correspond to the log of energy,  $GDP$  and investment price indexes,  $EDUC$  is the average years of schooling,  $ER$  is the employment rate. The indexes  $c$  and  $t$  (or  $t-1$ ) indicate the country and the year.  $FE_c$  is a country fixed effect. The economic convergence is introduced with  $I_{T,t} = \text{Max}(0; t-T)$  for year  $T$  and  $\delta t f p_c = \delta q_c \times (1 - \alpha)$  the coefficient of convergence obtained from the convergence modelling equation in Section 2.2. The country-specific values  $\delta t f p_c$  are detailed in Table 2 in Appendix 2.

The country fixed effect depends on anti-competitive regulations and is estimated through the relation (3b):

<sup>5</sup> In this estimated equation and the following estimated ones, \*:  $p < 0.05$ ; \*\*:  $p < 0.01$ ; \*\*\*:  $p < 0.001$ .

$$(3b) \quad FE_c = -0.108^* \cdot REGUL_c + \beta_0 + \varepsilon_c$$

Where  $REGUL_c$  corresponds to the regulation indicator.  $REGUL$  is the crossed product (PMR, for product market regulations) and labour (EPL, for employment protection legislation) regulation indicators from Koske *et al.* (2015) and OECD (2013).

The total final consumption of energy,  $TFC$ , is expressed in thousand tons of oil equivalent (*ktoe*) on a net calorific value basis. Depends also on several variables:

$$(5) \quad tfc_{c,t} = 0.965^{***} \cdot gdp_{c,t-1} + -0.670^{***} \cdot rpe_{c,t-1} + \mu_0 + \varepsilon_{c,t}$$

Where  $tfc$  is the log of the total final consumption of energy,  $gdp$  is the log of the GDP,  $rpe$  is the log of the relative prices of energy, and  $\varepsilon$  is the error term, for countries (or regions)  $c$  and year  $t$ .

$RPE$  is derived from the relative prices of each type of energy weighted by their respective shares in the total consumption of energy:

$$(4) \quad RPE_{c,t} = \sum_i [RPE_{c,i,t} \times \Omega_{c,i,t}] \text{ where } \Omega_{c,i,t} = \frac{TFC_{c,i,t}}{TFC_{c,t}}$$

Where  $\Omega_i$  is the share of the energy of type  $i$  in the total volume of the final energy consumption. To calculate the relative energy prices, we divide these data by the  $GDP$  deflator.

ACCL distinguishes five distinct types of energy: coal, oil, natural gas and electricity that are derived from both “dirty” (CO<sub>2</sub> emitting) and “clean” (non- CO<sub>2</sub> emitting) energy inputs.<sup>6</sup> Their respective shares in the total final consumption of energy are computed using equation (6).

$$(6) \quad \Delta\Omega_{c,i,t} = \Omega_{c,i,t-1} \cdot \sum_j [\Omega_{c,j,t-1} \cdot \sigma_{i,j} \cdot (\Delta rpe_{c,j,t} - \Delta rpe_{c,i,t})]$$

Where  $\Delta$  is the variation within the time interval considered and  $\sigma_{i,j}$  the pairwise elasticities of substitution between energy types, for all the various energy sources  $i \neq j$ .

To consider the economic consequences of climate change, the consumption of energy is translated into global carbon dioxide emissions according to the equation (7a):

$$(7a) \quad CO2_t = \sum_{i,c} TFC_{i,t,c} \cdot \gamma_i$$

Where  $CO2$  is the world carbon dioxide emissions (in tonnes of CO<sub>2</sub>) and  $\gamma_i$  the default emissions factors for energy type  $i$ .

ACCL uses a simplified carbon cycle employing the Permanent Inventory Method (PIM) to model the increase of the worldwide stock of carbon dioxide by the aggregate CO<sub>2</sub> emissions. Our PIM is depicted by the accounting relation (7b):

$$(7b) \quad StockCO2_t = (1 - \rho_1) \cdot StockCO2_{t-1} + (1 - \rho_2) \cdot CO2_t - \rho_3_t$$

Where  $StockCO2$  represents the worldwide stock of carbon dioxide (in giga tonnes of CO<sub>2</sub>),  $CO2$  the world carbon dioxide emissions (converted in giga tonnes of CO<sub>2</sub>), whereas  $\rho_1$  and  $\rho_2$  are the coefficients of CO<sub>2</sub> sequestration by the carbon sinks of the planet (*i.e.*, natural or artificial reservoirs capturing atmospheric CO<sub>2</sub>) as a fix proportion of the stock or the emissions and  $\rho_3$  another type of possible CO<sub>2</sub> sequestration independent to both emissions and stock of CO<sub>2</sub>. There appears to be no consensus in the scientific literature on the optimal way to model carbon dioxide sequestration or the precise value of its estimate. Therefore, ACCL offers the user the possibility to choose and modify the different coefficients at will. By default,  $\rho_1$  and  $\rho_2$  are

<sup>6</sup> As dirty means here CO<sub>2</sub> emitting, ACCL considers nuclear electricity production as a clean one, which could, of course, be contested from other dimensions.



null as we set a fixed amount of annual CO<sub>2</sub> sequestration equal to a third of the 2015 carbon dioxide emissions.

ACCL converts the resulting projections of CO<sub>2</sub> emissions stock in a global warming of the Earth and adopts for that the linear calibrated relation (8):

$$(8) \quad Temp_t = \eta_1 \cdot StockCO2_t$$

Where  $Temp$  is the increase in world temperatures from the pre-industrial era (in degrees Celsius) and  $\eta_1 = 0.0008$ .

Relation (9) describes how ACCL finally obtains the economic damage generated by climate change, defined as *“the fractional loss in annual economic output at a given level of warming compared to output in the same economy with no warming”*:

$$(9) \quad D_{c,t}^{GDP} = D_t^{GDP} \cdot \frac{\omega_c}{\omega} \text{ with } D_t^{GDP} = \theta_1 \cdot Temp_t + \theta_2 \cdot Temp_t^2 + \theta_3 \cdot Temp_t^4$$

Where  $D^{GDP}$  is the climate-induced damage as a percent of  $GDP$ ,  $\omega_c$  and  $\omega$  respectively the OECD (2015) regional and aggregate coefficients of climate-induced damage.

The world damage hence follows a four-degree equation with the temperature rise. By default, ACCL uses a quadratic relationship ( $\theta_3 = 0$ ), but the user can model tipping points in the damage function through  $\theta_3$ . The default values of the parameters are:  $\theta_1 = 0.38$  and  $\theta_2 = -0.48$ . This worldwide damage is then broken down into local damages using the share of the OECD (2015) regional coefficients of climate damage ( $\omega_c$ ) in the OECD (2015) aggregate coefficient of climate-induced damage ( $\omega$ )– both at the 2060 horizon of the OECD study, as a distribution key.

**Appendix 2****Table 2****Coefficients of economic convergence by country and region**

Countries and regions	Coefficients of convergence $\delta t f p_c$
Australia	0.0000
Austria	0.0005
Belgium	0.0007
Brazil	0.0066
Canada	0.0005
Switzerland	0.0009
China	0.0066
Germany	0.0017
Denmark	0.0015
Spain	0.0025
Finland	0.0015
France	0.0017
Great-Britain	0.0008
India	0.0118
Italy	0.0015
Japan	0.0029
South Korea	0.0028
Malaysia	0.0033
Mexico	0.0055
Netherlands	0.0004
New-Zealand	0.0016
Portugal	0.0027
Russia	0.0030
Sweden	0.0004
United States	0.0000
Africa	0.0134
Rest of Asia	0.0110
Central and Eastern Europe and Central Asia	0.0050
Rest of Latin America	0.0065
Middle-East	0.0034
Rest of Western Europe	0.0013

*The country-specific values of the economic convergence coefficients  $\delta t f p_c$  are computed following the equations in Section 2.2.*